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The Design of a Portable and Deployable Solar Energy System for Deployed Military Applications

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Abstract- **Global Positioning Systems, thermal imaging scopes, satellite phones, and other electronic devices are critical to the warfighter in Forward Operating Environments. Many are battery operated and require charging. We used a Systems Engineering approach to compare existing portable energy systems and to specifically design a portable solar energy system for use tailored for a deployed military/combat unit. We considered ease of setup/teardown, power delivered, weight, and many other factors that contribute to the level portability required. As deployed units are often in areas with little or no permanent sources of electricity, powering and/or charging electronic devices can be a challenge and diesel generators are the typical solution. Generators require fuel (approximately 1 gallon/hour for 10KVA) which is extremely costly in both money and safety of soldiers tasked with transporting fuel. Understanding the factors that affect portability and knowing which ones are the most important is key to determining whether a particular energy generation system is an asset or liability. Currently, there is no simple rubric to characterize what portability is and how to compare two systems. We therefore created a rubric to aid our analysis of portability. With such a set of measurements and procedures, designs can be meaningfully compared and once designed, we used the new metrics to improve our overall design. Several conceptual designs were drafted and compared, using the metric, to current diesel generators used by the U.S. military in both Iraq and Afghanistan. We identified areas where diesel generators are superior and areas where the solar energy systems are superior. The remainder of this paper outlines our process and results.**

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I. INTRODUCTION

THE Office of the Secretary of Defense (OSD) issued a grant to the U.S. Air Force Academy's Department of Electrical and Computer Engineering to develop a portable solar power system. Additionally, other organizations are interested in advancing renewable energy technology for use by the military. For example the Defense Advanced Research Projects Agency (DARPA) is funding research to develop a lightweight durable and highly efficient solar cell that can handle the rigors of deployed military use [1]. The National Renewable Energy Laboratory (NREL) has similar goals of designing soar panel systems that are reliable and durable for use by government agencies [2]. The goal of this design program is not to develop a sturdy and highly efficient solar cell, but rather to design an entire system that contains highly efficient cells that are currently on the market. The system will include a battery bank, inverters, a monitoring system, and a control interface. Included in the functionality of the design is grid-tie. For the foreseeable, future Forward Operating Bases (FOBs) will not be able to rely on solar energy alone. Therefore during the phase-in process this solar panel design must operate effectively with pre-existing sources of energy such as diesel generators. The importance of portability cannot be emphasized enough in the realm of deployed systems. The portability study sought to find the tangible design variables that can be adjusted to create a solar panel system that epitomizes portability. By including electrical component selection and performance requirements in the design considerations, the design constraints are developed.

II. METHODOLOGY

The initial and only requirement for the portable system was that it output 10KVA of power. This single technical requirement is not nearly enough to build a design off of, so the team became responsible for conducting the research necessary to establish adequate design requirements based

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14. ABSTRACT

Global Positioning Systems, thermal imaging scopes, satellite phones, and other electronic devices are critical to the warfighter in Forward Operating Environments. Many are battery operated and require charging. We used a Systems Engineering approach to compare existing portable energy systems and to specifically design a portable solar energy system for use tailored for a deployed military/combat unit. We considered ease of setup/teardown, power delivered weight, and many other factors that contribute to the level portability required. As deployed units are often in areas with little or no permanent sources of electricity, powering and/or charging electronic devices can be a challenge and diesel generators are the typical solution. Generators require fuel (approximately 1 gallon/hour for 10KVA) which is extremely costly in both money and safety of soldiers tasked with transporting fuel. Understanding the factors that affect portability and knowing which ones are the most important is key to determining whether a particular energy generation system is an asset or liability. Currently, there is no simple rubric to characterize what portability is and how to compare two systems. We therefore created a rubric to aid our analysis of portability. With such a set of measurements and procedures, designs can be meaningfully compared and once designed, we used the new metrics to improve our overall design. Several conceptual designs were drafted and compared, using the metric, to current diesel generators used by the U.S. military in both Iraq and Afghanistan. We identified areas where diesel generators are superior and areas where the solar energy systems are superior. The remainder of this paper outlines our process and results.

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off the needs of the user. A basic but monumental amendment was quickly made to the original requirement of 10KVA. This requirement was further defined by the team that it be capable of outputting 10KVA for 6 hours continuously without sunlight. This new design requirement meant including a battery bank or a fuel generator in the design since solar panels are inherently incapable of 24 hour power generation. Because the purpose of this design includes reducing the use of fuel in the FOB environment, the decision was later made to use a battery bank. Solar panels Generate direct current requiring the use of an inverter because the standard current type for American electronics is alternating current, and the inverter serves to solve this problem. A major part of the system's design is its incorporation into a preexisting network of AC power sources, a task known as "grid tie" or "smart grid". In order to match this requirement the team acquired a battery bank that simulates the flow of power that would be experienced by the system being designed. "Smart grid" for our purposes is informed and efficient distribution of power to serve customer needs more effectively while decreasing cost. This is achieved through monitoring general power usage to determine the most advantageous periods to:

1) decrease customer energy costs by supplying power from the solar power system rather than the power grid during times of peak usage,

2) charge battery bank when either utility power cost is cheapest or from a lull in customer power consumption where the solar power system can divert its output power to charge the batteries

3) increase total output power of the system combining output from the batteries with solar or utility power to supply power to any short unexpected increases in customer energy consumption.

Efficient smart grid will be achieved through understanding the limits of the battery bank, constant communication between current solar power system data and previous data, and having and understanding customer load profiles. This information provides triggers for the solar system to change configuration of how the system is supplying power to the users.

The portability study provides the measurements necessary to evaluate portable power systems. Using the established rubric, preliminary design concepts can be eliminated, and later prototypes can be heavily scrutinized and refined into perfected initial systems. These systems will then set the initial standard for portability and efficiency for all future designs to surpass. The current application of the rubric is in tradeoff analysis of internal components, and refinement of conceptual designs for the stowing and deployment methods of the solar arrays.

The requirements given by OSD were quite open ended, requiring the team to research real-world conditions faced in the field. Embracing the essence of systems engineering, the requirements of the system were derived from the needs of the customer. A division of the Air Force's Civil Engineering corps, Rapid Engineer Deployable Heavy Operational Repair Squadron Engineers (RED HORSE) is tasked with rapid deployment and set up of FOBs and structures. Members of this elite engineering corps were consulted as customers to find attributes that would be both necessary and useful in a system such as the one being developed. From this consultation, a requirement was developed specifying that the system fit into a CONEX container. However, after the components of the system were compiled, the size of a CONEX box (20' x 9' x 8.5', total internal volume of 1530 ft^3) was far too large to be practical as a standard of volume for the system. As a result a requirement became to minimize the volume of the system.

The initial weight requirement was constrained by the pulling capacity of a Humvee. The pulling capacity is 1 ton (2000 lbs) which then became the requirement for the maximum, overall weight of the system. After an exhausted parts list was compiled, an overestimate of the total weight was made, measuring far short of the 1 ton limit (600 ± 100 lbs). Again the requirement was met with ease, and allowed the team to focus on minimizing the total weight.

Maximized portability and power output and endurance are the core objectives of this project. To create a design that meets the customer's needs the most is the best design that can be created. The focus during the design phase of this system is on tradeoff analysis. The big three for project management of price, quality, and time are a given. There is no set delivery date for this product, there are however limits on the amount of money available for development ($100k), and since this system is being built for our comrades in arms, this team holds itself to creating a system with the greatest quality that can be provided.

The first unique tradeoff element of this design, is maximizing portability; as the robustness of the design increases, the portability decreases. Any time a component is added giving new or increased ability to the system, its weight or size increases, inadvertently making the system less portable. The first and most important place that this tradeoff is encountered is selecting the size and type of solar panels used for charging the battery bank. During research lightweight and flexible solar panels were sought out. One supplemental benefit of these panels is the ability to add or subtract the number of solar panel units necessary for the mission. This gives a greater deal of control to the user and a dimension of leeway for the designer.

Next is the decision of what batteries should be used in the battery bank. The two best battery types are lead-acid and lithium-ion. There are several tradeoffs here to consider. Lithium-ion batteries are significantly lighter and charge faster. Lead-acid batteries have a much larger current capacity, which is essential for outputting over a long period of time like the 6 hours that is required of the system. Lead-acid batteries have a longer useful life as well, making scheduled and unscheduled maintenance less frequent than its lithium-ion counterpart.

Since this system is to be deployed alongside soldiers in rugged areas such as Afghanistan, durability is essential for the system to be reliable. Increased durability means denser materials, and more protective surfaces, which causes increased weight and volume, and once again takes away from the level of portability.

Bare essentials for the durability of the system include hardened air tight covers for the electrical components. A sturdy stowing structure so the material can handle the rigors of transportation in the field. The stowing structure will be either a custom trailer, or a metal box. The system will need bracing harnesses inside of the stowing structure to minimize jostling of components during transportation. This stowing structure is designed with the possibility of airlift insertion in mind.

While overall weight of the system is heavily looked at, other metrics must be considered for maximizing the portability of the system. Time to deploy/stow and effort to deploy/stow are two metrics that have a different relationship with portability

Table 1: Portability Metrics

1. Weight or mass
2. Moment of inertia in stowed versus deployed state
3. Position of CG
4. Largest dimension in a stowed state
5. Ratio of largest deployed dimension to largest stowed dimension
6. Volume or compactness in stowed state
7. Ratio of volume in deployed state to volume in stowed state
8. Cross sectional area in stowed state
9. Ratio of Cross sectional area in deployed state to cross sectional area in stowed state
10. Largest diagonal in stowed state
11. Ratio of largest diagonal in deployed state to largest diagonal in stowed state
12. Effort to deploy/stow
13. Energy or work expended to deploy/stow
14. Power needed to deploy/stow
15. Energy density with respect to mass/volume/largest dimension
16. Time to deploy/stow
17. Number of steps to deploy/stow
18. Number of individual components

III. Considerations for the Future

A very large amount of the work done thus far by this capstone program has had to do with developing the requirements. Making requirements that are feasible for the engineer to meet, satisfy the customer, and useful can be quite a challenge. Designing a potable solar panel has several unique challenges to it. First, with current political pressure to develop effective renewable energy technology the efficiency, durability, and size of solar panels are constantly getting better. Such rapid advancement in technology can severely impact the design of the system with regards to the power requirement, especially the deployment and stowing methods.

Environmental testing will be essential for this system prior to its critical design review. If the system were going to be used in softer and friendlier conditions than FOBs in dessert and rugged terrain, this would not be such an essential part of the design process. However it must be emphasized that reliability is essential and rugged environment is a huge reality for the user.

References:
1. DARPA looking for solar cells that can withstand the rigors of war. Homeland Security Newswire, June 2010
2. National Renewable Energy Labs, Solar
3. Concorde PVX-3050 Sun Xtender battery Data Sheet
4. PowerFilm Rollable Solar Film Data Sheet
5. PowerFilm Rollable Chargers Data Sheet
6. Tactical Quiet Generators, Global Security.org
7. Mobile Solar Power Systems at a Glance, Pure Power Distibution
8. National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401. (PV System Operation and Maintenance Manual)
9. Kronenburg, Robert *Portable Architecture,* Architectural Press, 2003 - Architecture - 274 pages
10. Kronenburg, Robert *Transportable environments,* Taylor & Francis, 1998
11. Kronenburg, Robert, Klassen, Filiz, *Transportable environments 3,* Taylor & Francis US, 2005 - Architecture
12. Kronenburg, *Ephemeral Portable Architecture,* John Wiley & Sons, 1998
13. Siegal, Jennifer More Mobile: Portable Architecture for Today, Princeton Architectural Press, 2008
14. Siegal, Jennifer *Mobile: The art of portable architecture*, Princeton Architectural Press, 200
15. Kamrani, Ali K., Salhieh, Sa'ed M., *Product Design for Modularity,* Springer, 2002 - Technology & Engineering
16. Dieng, Rose, *Designing cooperative systems: the use of theories and models : proceedings* section on design of mobile systems, IOS Press, 2000

17.Gemperle, F.; Kasabach, C.; Stivoric, J.; Bauer, M.; Martin, R.; "Design for wearability"
Inst. for Complex Eng. Syst., Carnegie Mellon Univ., Pittsburgh, PA, Wearable Computers, 1998. Digest of Papers. Second International Symposium on; 19-20 Oct 1998

*18.*Brebbia, C.A., *Mobile and Rapidly Assembled Structures II,* Built Environment volume 24, Wessex Institute of Technology, United Kingdom & F.ESCRIG, University of Seville 1996

19. Dowlatshahi, S. "The role of logistics in concurrent engineering" Department of Information and Decision Sciences, College of Business Administration, The University of Texas, El Paso, TX 79968-0544, USA, October 199

*20.*Boarnet, Marlon, Crane, Randall *Travel by design: the influence of urban form on travel,* Oxford University Press US, 2001

21.Dowlatshahi, Shad "Theory and Methodology, A modeling approach to logistics in concurrent engineering", Department of Information and Decision Sciences, College of Business Administration, University of Texas at El Paso, El Paso, TX 79968-0544, USA Received 21 July 1997; accepted 30 October 1997

22.Karwowski, Waldemar, Salvendy, Gavriel, *Ergonomics in manufacturing: raising productivity through workplace improvement*, SME, 1998 - Technology & Engineering

23.Stanton, Neville *Handbook of human factors and ergonomics methods,* CRC Press, 2005 - Technology & Engineering

*24.*Kumar, Shrawan, Mital, Anil, *Electromyography in ergonomics*

25.Stanton, Neville *Human factors in consumer products*, CRC Press, 1998, Technology & Engineering

26.Lehto, Mark R. , Buck, James R. *Introduction to human factors and ergonomics for engineers*, CRC Press, 2007 - Technology & Engineering - 969 pages

27.Karwowski, Waldemar *International encyclopedia of ergonomics and human factors, Volume 3*, Taylor & Francis US, 2001

28.Land, P. "Lunar Base design", Lunar Bases and Space Activities of the 21st Century. Houston, TX, Lunar and Planetary Institute, edited by W. W. Mendell, 1985,

29.Salama, M., Lou, M., Fang, H., "Deployment of Inflatable Space Structures: A Review of Recent Developments.", Jet Propulsion Laboratory, AIAA-2000-1730

30.Cassapakis, Constantine *G.*, Love, Allan W., Palisoc, Arthur L., "Inflatable Space Antennas A Brief Overview", IEEE, 1998

31.Palisoc, Arthur L., Huang, Yuli, "Design Tool For Inflatable Space Structures" AIM-974 378,

32.Cadogan, David, Scarborough, Stephen E., "Rigidizable Materials for use in Gossamer